

Nuclear Energy Basics Notes

This presentation addresses the economics, science, and facts of nuclear energy.

Slide 3 – how a fossil-fuel power plant generates electricity graphic

- fossil fuel heat source for conventional steam cycle power plant (heat = thermal energy)
- fuel burned in boiler (furnace)
- heat boils water flowing in cooling tubes in boiler wall to create steam
- steam directed to steam turbine where thermal energy converted to mechanical energy
- mechanical energy converted to electrical energy by electrical generator connected to steam turbine shaft
- low-pressure, low-temperature steam exiting steam turbine condensed back to water in condenser and pumped back to boiler to start cycle over again

Slide 4 – how boiling water reactor generates electricity graphic

- nuclear reactor is heat source for conventional steam cycle power plant
- nuclear fuel produces heat in nuclear fission process
- heat boils water flowing around nuclear fuel rods

Slide 6 – hydrocarbon vs nuclear energy production

- slide shows calculation of energy released from combustion (burning) of methane (primary component of natural gas) and fission of U-235 (isotope of uranium that fissions)
 - energy released in combustion results from rearrangement of molecular electron bonds in chemical reaction
 - energy released in fission results from decrease in nuclear binding energy when U-235 nucleus splits into two smaller fission fragment nuclei
- ΔH_f – heat of formation
- kilojoules and million electron-volts are units of energy
- don't worry about different units used to express energy, whether it's joules, calories, British thermal units (BTU), or electronvolts; can always look up definitions and find conversion factors for converting one unit into another; what's important is that same units used when making energy comparisons
- energy from U-235 fission releases 1.5 million times more energy from atomic nucleus than rearranging of electron bonds from combustion of methane (largest heat of combustion of all hydrocarbons)

Slide 7 – energy content of fuels

- slide shows specific energy (energy per unit mass) of natural gas, crude oil, and coal same order of magnitude
- U-235 specific energy 1.5 million times more than hydrocarbon fuels

Slide 11 – source energy equivalents

- energy equivalents shown in graphic correspond to fuel pellet with approximately 5% enriched uranium (natural uranium enriched in U-235 isotope)

Slide 14 – $E = mc^2$ illustrated

- key to nuclear fission – extra neutrons (usually 2 or 3) to sustain chain reaction
- end products of fission events are lighter isotopes called fission fragments
- U-235 fission releases about 200 MeV of energy from splitting of nucleus
- 5 MeV gamma-ray emitted when U-235 becomes U-236 in non-fission neutron capture event ($\approx 15\%$ of the time)

Slide 15 – fission energy constituents

- fission fragments, liberated neutrons, radiation consisting of beta particles and gamma-rays
- a few fission fragments emit neutron following beta decay to excited daughter state

Slide 17 – fission fragment distribution

- bimodal distribution with most probable ($<10\%$ yield) fission fragments having atomic mass numbers of 95 and 137
- decay chains for radioactive fission fragments Sr-94 and Xe-140 illustrated (decay by beta particle emission)

Slide 18 – radioactivity

- primary decay modes for fission products are beta particle, most times with accompanying gamma-ray emission
- alpha particle emission occurs with decay of very heavy isotopes like U-235 and U-238

Slide 19 – radioactive half-life

- time required for quantity of radioactive material to be reduced by one-half its original value
- characteristic curve for all radionuclides – undecayed amount plotted as function of number of half-lives
- all radionuclides have characteristic half-life, some long, some short
 - 4.5 billion years for U-238
 - 20 minutes for C-11

Slide 22 – fission neutron multiplication

- illustrates neutron multiplication with each neutron generation in chain reaction
- fission reactions increase exponentially generating more and more energy
- chain reaction must be controlled to obtain only degree of nuclear fission (energy generation) desired

Slide 23 – controlling chain reaction

- control rods made of neutron absorbing material used to achieve and maintain stable neutron population in nuclear reactor core
- stable neutron population is critical (self-sustaining) reactor configuration

Slide 24 – 3 possible neutron population conditions in nuclear reactor

- subcritical – condition during reactor startup and shutdown
- critical – normal operation at power
- super-critical – condition to be avoided

Slide 26 – neutron moderation

- concept of interaction cross-section – effective cross-sectional area of spherical nucleus proportional to probability of interaction with incident neutron

Slide 27 – U-235 fission cross-section vs neutron energy graphic

- graphic shows how fission cross-section of a U-235 atom varies with neutron energy
- note log scales on both axes
- cross-section unit called barn = $1 \times 10^{-24} \text{ cm}^2$
- neutrons liberated by fission events have average initial energy of about 1 MeV
- U-235 fission cross-section for 1 MeV neutron about 1 barn

Slide 28 – same graphic

- U-235 fission cross-section 580 barns for neutrons with energy of 0.025 eV
- 0.025 eV neutrons essentially in thermal equilibrium with surroundings – called thermal neutrons or slow neutrons

Slide 31 – neutron scattering events graphic

- neutron loses some or most of its energy in collision with hydrogen nucleus (visualize collision of 2 billiard balls)
- neutron loses very little energy in collision with heavy nucleus (visualize collision of ping pong ball with bowling ball)

Slide 32 – neutron moderation in reactor illustration

- graphic depicts 3 uranium fuel rods with intervening moderator/coolant channels and illustrates how — high energy fission neutron escaping from fuel matrix loses energy in moderator/coolant

- slow neutron re-entering fuel matrix either causes fission of U-235 nucleus or is captured in non-fission event by U-238 nucleus

Slide 33 – moderator effectiveness

- all reactor core materials experience interactions with fission neutrons
- some better neutron moderators than others
- water and heavy water very effective neutron moderators

Slide 36 – decay heat vs time after reactor shutdown graphic

- note log scales on both axes
- at reactor shutdown, decay heat amounts to 7.5% of heat generated at full reactor power
- at one month following shutdown, decay heat still generating about 0.1 % of full reactor power heat load

Slide 38 – nuclear waste – used fuel

- political problem, not technical problem
- for comparison, if Connecticut Yankee had been coal plant, toxic ash waste on same pad would make column 7000 feet high

Slide 39 – used nuclear fuel dry storage cask graphic

- used nuclear fuel assemblies stored in air-cooled dry storage casks at nuclear plant site

Slide 40 – used nuclear fuel content graphic

- incorrectly designated as waste
- left cylinder – represents 3% enriched new reactor fuel
- right cylinder – represents fuel following 4 years in reactor core producing power
- 97% of used fuel consists of reusable material (U-235, U-238, Pu)
- only 3% actually waste material

Slide 42 – high-level radioactive waste decay

- high-level waste from used reactor fuel consists of two distinct components --- fission products and actinide element isotopes
- actinide isotopes, primarily plutonium, neptunium, americium, and curium, are activation products created by non-fission capture of neutrons in U-238
- radioactivity of high-level nuclear waste becomes less than that of original uranium ore in less than 10,000 years
- using accelerators to transmute high-level nuclear waste would reduce radioactivity to less than original ore in very much shorter time period

Slide 43 – used fuel element radiation doses

- figure shows alpha (non-penetrating), beta (weakly penetrating), and gamma-ray (photon) radiation dose rates (mGy/d) at surface

of used nuclear fuel element beginning at year 10 following removal from nuclear reactor

- dashed red line shows dose rate at 2 meters from used fuel element surface (effectively gamma-ray dose as alpha and beta particles cannot penetrate fuel element cladding)
- note that most high energy gamma-ray emitting radionuclides have decayed away in about 600 years (solid red line)
- remaining long half-life alpha-emitting actinides and beta-emitting fission products do not present significant external health hazards, due to weak penetrating power of alpha and beta particles
- for reference purposes: after 600 years of radioactive decay, contact handling of a fuel element for relatively short periods of time (at most a few hours) would result in whole-body dose at least an order of magnitude below high acute dose threshold for potential harm

Slide 45 – long-term storage of un-reprocessed nuclear fuel

- costs of proposed long-term storage of un-reprocessed used nuclear fuel using fracking technology alleged to be much less than geologic repository, which was killed by anti-nukes in Congress after spending billions of dollars
 - most, if not all, used nuclear fuel could be stored safely onsite instead of having to be transported to central repository
 - could be recovered later for use in breeder reactors
- costs for building expensive hot cells to repackage used fuel from existing dry storage canisters into borehole-compatible formats may be prohibitive
- question is, why repackage for burial when we could reprocess for reuse

Slide 46 – nuclear fuel reprocessing graphic

- graphic illustrates what America should be doing with used nuclear fuel
- reprocessing separates material into intermediate level waste (fuel rod cladding, etc.), high level waste (fission products), and usable uranium and plutonium streams
- President Carter banned reprocessing used nuclear fuel and instantly made Barnwell nuclear fuel reprocessing facility worthless (industry had invested about half a billion dollars and facility was nearing completion)
- although President Regan lifted reprocessing ban, nuclear fuel recycling industry can be destroyed with stroke of presidential pen – a risk no company willing to take

Slide 49 – world used nuclear fuel reprocessing capacity

- France, Britain, Russia, and India all reprocessing used nuclear fuel for long time (Japanese Rokkasho-Mura plant licensed, but not yet operating)
- these countries don't have nuclear proliferation concern that prevents used nuclear fuel reprocessing in U.S. (because it's political issue, not real issue)
- federal government took control of destiny of used nuclear fuel with 1982 Nuclear Waste Policy Act; no political will to change that

Slide 50 – nuclear resource and high-level waste comparison graphic

- golf ball represents amount of nuclear material required to generate electricity needs for one person's lifetime
- coke can represents resulting amount of nuclear waste from reprocessed nuclear fuel requiring managed disposal
- volume of waste exceeds original resource volume due to additional materials needed to permanently immobilize high-level waste fission products

Slide 53 – annual waste from electricity-generating power plant operation

- annual waste produced generating 1000 megawatts of electricity with fossil fuel and nuclear fuel shows quite contrast in both total quantity of waste (second column from right) and quantity per kilowatt-hour of electricity generated (column on right)
- no gaseous or small particulate matter emissions from operation of nuclear power plants

Slide 54 – life-cycle waste comparisons

- politically-biased discussions of electrical-generating system waste generally focus only on waste generation from facility operations, ignoring activities required for facility construction, maintenance, and ultimate demolition
- electrical-generating facility must be constructed with materials and provided with equipment manufactured from resources that must be mined, refined, and transported --- activities that generate waste
- equipment for transmitting electricity to grid also involve mining, refining, manufacturing, transportation, and construction activities that generate waste
- end-of-life equipment and failed equipment must be disposed of as waste material
- when facility has reached end of useful life, must be demolished and all demolition materials must be recycled or disposed of as waste

Slide 55 – life-cycle emissions

- table shows life-cycle gaseous and particulate emissions per kilowatt-hour of electricity generation for all energy resources used to generate electricity
- nuclear energy stands out as one of cleanest resources for generating electricity
- notwithstanding differing measurement units, life-cycle waste can differ drastically from operational waste

Slide 57 – land requirements for generating 1000 Mw of electricity

- numbers for PV and wind facilities vary significantly in literature, depending on assumptions being made
- nonetheless, contrast of land requirements is evident

Slide 58 – visual illustrating land requirements for wind and solar to substitute for current nuclear energy production in U.S.

Slide 59 – land area needed to power flat-screen TV visual

Supplemental slide information

Slide 62 – medium half-life (5-90 years) fission products

- Sr-90 and Cs-137 health hazards due to high decay energy

Slide 63 – β , γ decay graphic

- some radioisotopes decay by particle emission directly to ground energy state of daughter nucleus
- others decay by particle emission to elevated energy state of daughter nucleus, which subsequently emits gamma-ray to get nucleus to ground energy state
- some radioisotopes, like Cs-137 shown in graphic, experience both decay events with different probabilities of occurrence

Slide 64 – long half-life (211,000 – 15.7 million years) fission products

- tin-126 (Sn-126) high decay energy not health concern as very little produced by U-235 fission

Slide 65 – binding energy per nucleon graphic

- graphic illustrates energy liberated in fission and fusion reactions, called binding energy because it's energy that binds protons and neutrons together in atomic nucleus
- figure shows maximum binding energy per nucleon (i.e., per particle in nucleus) is about 8.8 million electron volts ($\approx 1.6 \times 10^{-13}$ Joules), which is typical of “iron group” of isotopes